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Session 1 Paper and Presentation - Wave Buoys: Using the Right Tool for the Right Job

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Wave Buoys: Using the Right Tool for the Right Job

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***Abstract*—**Wave buoys measure water level fluctuations that are caused by astronomical forces, winds, and events such as glacier slides. There are also many types, sizes, and configurations of wave buoys since they may be used for a variety of purposes. They are large and small, directional and non-directional, and drifting and moored. Buoy selection should be determined based on environmental conditions associated with the deployment location and information needs. Modern wave buoys measure and transmit automatically, in a predictable and controlled way, communicating in real time via radio, cell phone, or satellite. All wave buoys measure the frequency and amount of wave energy, usually the wave height. More sophisticated wave buoys are used to determine wave height, period, and direction. Information from properly sited wave buoys improves severe weather forecasting.

1. Introduction

Today's marine research and operations managers are confronted by a sometimes bewildering array of wave-measuring buoy systems. Buoys come in a variety of sizes and shapes, mooring methods and configurations, sensor types, communication and data processing systems. Some can be hand-deployed by one or two people, while others require onboard cranes and a dedicated crew. Prior to purchase, fabrication and deployment, users need to fully understand their requirements, which include environmental factors, hardware and software capabilities, and limitations prior to sourcing the wave buoy that is optimal for their needs.

Wave sensors for buoy deployment generally include accelerometers or GPS receivers, compasses, with associated computer processors, power supplies, and communication equipment [1]. The buoy must measure all components of motion needed to obtain wave data. Wave buoys can provide users with non-directional or directional wave data. Directional wave buoys require additional sensors to measure the tilt, and possibly the curvature of the sea surface. All wave measuring buoys report wave height and period, or wave height, period, and direction, from which the data products that the user desires can be derived.

Buoy developers have designed an array of hull forms and moorings to survive deployments in the marine environment. There are small air-deployed wave buoys, larger coastal buoys, and heavy and durable deep sea wave buoys. Some examples are provided in Fig. 1 [2].

2. Buoy Types Based on Deployment Locations

Buoys can be categorized based on where they are deployed. They are usually designed to measure directional wave properties and can usually be deployed from a vessel by a team of 2 to 8 people. Buoys designed for smaller and/or protected bodies of water can be smaller, lighter, and will be easier to handle. More robust buoy systems are found in coastal waters. The smallest buoys are lightweight, easily transported, deployed, and retrieved by hand from a small boat with a one- or two-person crew, usually for short durations of hours to days.

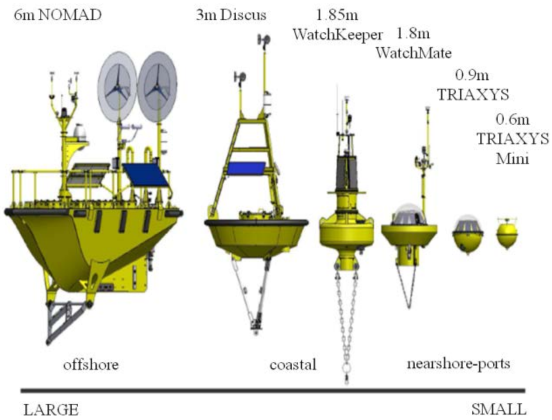

Figure 1. Wave buoy sizes and shapes.

Coastal wave buoys, and buoys suitable for deployment in lakes and rivers are of larger size than hand-deployable variants. They require strong mooring tackle, and reliable and rugged components, and either line-of-site radio or cell phone communications. They are deployed into the coastal ocean using ships equipped with cranes under the guidance of a Deck Chief and several deck hands. National Oceanic and Atmospheric Administration (NOAA) buoys that comprise the National Data Buoy Center (NDBC) Ocean Observing System of Systems are often serviced using U.S. Coast Guard Cutters (USCGCs). Fig. 2 is a picture of USCGC ASPEN that services NOAA buoys sited along the central California coast

Figure 2. Buoy tender in San Francisco Bay.

Deep sea wave buoys are heavy with diameters of approximately twelve meters or so. Some of the earliest deep sea buoys were of the doughnut type, such as the Richardson buoy (now known as toroidal buoys), disk shaped, such as the Monster buoy, or boat-shaped, such as the NOMAD (Navy Oceanographic Meteorological Automatic Device) buoy. These buoys require extensive mooring tackle for deployment in depths of 4,000 m or more and great survivability. They may be deployed from months to years. Usually, RF data transmission via satellite is employed, but many buoys are equipped with internal digital recorders in case communications are severed due to severe weather or other damage. In some cases, internal data recording is more detailed than the real-time transmissions, and suitable for subsequent scientific analysis.

In most deployments, raw data are usually processed onboard the buoy and then transmitted as wave height, wave period and direction, and ancillary parameters such as temperature, salinity, current speed and direction, wind speed and direction, as well as engineering data to assure that the buoy is responding correctly.

The most useful wave buoys, regardless of size, make wave data available immediately after acquisition and processing, via a communication system such as a VHF radio modem which may be line-of-site for coastal buoys, or RF linked to a satellite, and connected through the Internet, where it can be made immediately available to users. In a few cases, near-shore buoys are hard-cabled to an ocean observatory or a station on shore. Sub-surface buoys using pressure gauges, or “inverted fathometers” to sense the sea surface may use acoustic transmission to send the data to a surface buoy equipped with receiving hydrophone and decoder to transfer the data to an RF link for transmission to the users.

Design fundamentals depend heavily on the intended application, whether near-shore or deep sea, for short or long deployment, for severe or moderate currents and sea states, and for the possibility of icing, biological fouling, chemical corrosion, and so forth. In today’s global economy and consequent high volume marine traffic, survivability in the event of collisions or near collisions with ships may be an important design consideration; as well as resistance to vandalism or unauthorized tampering. The chosen design for the buoys and sensors must allow for good functionality and reliability under a variety of conditions. Sensors must be able to function in all situations of interest. Wind sensors that are destroyed by hurricane winds are of no value to the user.

Directional and nondirectional buoys are deployed for various applications. Nondirectional buoys are simpler, cheaper, have been in use for many years, and are the system of choice if only wave height and period are required. Directional buoys require additional sensors, more complex and costly data processing and analysis, and final archiving. In many cases in the past, however, nondirectional buoys were used when directional data were really needed because of limitations with the technology. Reliable, cost-effective directional buoys are a fairly recent development in oceanography [3].

3. Diameter, Shape, and Size

Wave buoy users that depend on processing software that converts buoy motions to wave motions are immediately confronted with issues surrounding the wave spectrum. The buoy must follow the motion of the water particles at the surface in the vertical (z) and horizontal (x,y) directions. Owing to the finite size of the wave buoy, it will not be able to follow waves that are smaller than the buoys approximate diameter. Thus, the limiting frequency is called the cut-off frequency and is a function of the diameter; hence the shortest wavelength that a buoy can follow is determined by the size of the buoy. Furthermore, the shape of the buoy determines its responsiveness to vertical wave motion. For example, strong resonances at the immersion frequency result in overestimated vertical motions for elongated buoys. Mooring lines can induce response phenomena associated with horizontal wave motions, Buoy rotations are of importance for wave motion sensors that are placed outside the buoy center of rotation, such as GPS. In this respect, determination of the pitch-roll resonance frequency is important. The vertical dimension of the buoy is also of importance since wave motions diminish with depth. Measurements from the deeper parts of the buoy will not be equal to those taken at the surface.

Wave buoy measurements will be confounded by breaking seas, where the hull is subjected to large accelerations. Under such conditions, the measurements may overestimate or underestimate the actual wave heights. The mooring tackle or tethering line must be designed to minimize distortions of the free floating buoy motions.

In summary, a buoy suited to measuring low-frequency tides will do a poor job of recording high-frequency gravity waves. The size, shape, buoyancy and weight are immediate constraints on the buoy frequency response. The frequency responses of the individual sensors must also be matched to that of the buoy to provide the desired high quality data. Dimensions for some standard buoys that are used operationally are listed in Table 1.

Table 1. Standard Buoys currently in use, worldwide.

Name	Standard Buoys		
Brand Name	Basic Shape	Diameter	Weight
Waverider	Spherical	0.9m	212Kg
TRIAXYS™	Spherical	1.10m	197Kg
Wavescan	Saucer	1.76m	710Kg
Mini Waverider	Spherical	0.40 m	17Kg

4. Sensors

A great variety of sensors are available to the user for the measurement of waves. Primary wave sensors include accelerometers, flux gate compasses, rate gyros, pressure gauges, wave staffs, upward looking acoustic sensors. GPS buoys do not use accelerometers. Instead, they use the Doppler shift in the GPS signal to determine the velocity of the GPS receiver relative to the satellites. When the GPS receiver moves toward (away from) the satellite it experiences an increase (decrease) in the GPS signal frequency that is proportional to the velocity of the buoy. Integrated over time this Doppler shift yields the relative buoy displacements.

Ancillary sensors include thermistor temperature gauges, conductivity sensors, current speed and directions sensors, such as acoustic Doppler profilers, wind sensors such as anemometer cup and wind vane, acoustic or laser wind profilers. All have advantages and disadvantages. Wave staffs are not seen very often on today's oceanographic buoys because of greater vulnerability and maintenance requirements, pressure gauges are also not often used because of the attenuation of high frequency waves with depth. Most wave buoys probably use accelerometers in height only measurements, and accelerometers, flux gate compasses, and rate gyros in directional buoys.

Ideally, individual testing and calibration of sensors should be done in a laboratory or wave tank, and then tested as an entire system on the buoy in the field. Issues with calibration-sensor calibration, including onboard calibration under the limit of expected environmental conditions should be uncovered and corrected during this testing phase.

5. Power and Maintenance Requirements

Most buoys today are powered by internal batteries; battery life can be considerably extended by means of solar collectors (Fig. 3). Short deployments of small buoys, such as for military purposes can be powered with high-technology non-rechargeable batteries; long duration deployments, such as for monitoring or providing navigation information can be powered with rechargeable batteries that can be recharged during periods of regularly scheduled maintenance. State-of-the-art buoys use solar panels to recharge the batteries, thus providing greatly extended battery life, and opening up opportunities for much longer buoy deployments. Maintenance requirements can vary greatly depending on the harshness of the environment, and the likelihood of collisions with commercial vessels, or damage due to vandalism.

6. Deployment Methodologies

Most drifting and moored wave buoys are deployed by merchant or research vessels from the lowest deck or ramp. Deployment methodologies vary greatly depending on buoy size, duration of deployment, severity of environmental conditions. The buoy is usually deployed first, followed by mooring line and then the anchor (Fig 4). Small buoys can be deployed from small boats with a small team, perhaps with divers (Fig. 5); coastal buoys will require winches and a few strong mariners, deep sea buoys may require buoy tenders, specialized vessels with cranes or A-frames, and a trained deployment team. Deck space must be allowed to flake out the mooring line and tackle in the proper deployment configuration in either buoy first or anchor first procedures. Then the deployment team can get inventive as logistics dictate.

Figure 3. Close-up picture of a solar powered WatchMate™ Buoy.

Figure 4. TRIAXYS™ Directional Wave Buoy with ADCP Launch.

Figure 5. Wave buoy deployed with a canoe off of Ghana.

7. Data Processing

Onboard the wave buoy all of the basic wave measurements are derived in some way from the estimated energy spectra of a time series of buoy motion. For nondirectional wave buoys, an accelerometer measures wave height by recording the vertical acceleration of the buoy as it rises and falls with passing waves. Double integration of the acceleration produces the time series of wave height. Directional wave measurement systems require in addition to the measurement of vertical acceleration or heave (displacement), buoy azimuth, pitch and roll. These allow east-west slope and north-south slope to be computed. Processing of the collected data is accomplished by spectral analysis and the zero crossing method, where parameters such as significant wave height, peak wave period, and average wave period are derived for the buoy location [4].

The most useful buoys today transmit desired data and data products in real-time. This capability requires onboard processing and computing. A sampling strategy must be devised to provide the data and data products at the required time increments.

Quality control algorithms must be built into the data processing algorithms. Noise bursts, missing data, outliers, and other bad data points must be edited out before the data can be released for application.

Data displays must allow for a quick assimilation of the environmental picture in order to give managers the needed information in time to take action. Examples would include optimal ship tracking, military go/no go criteria, and air-sea rescue operations. The real-time data might profitably be backed up by onboard recording for more detailed analysis at a later time.

The onboard-recorded data is often at a higher sampling rate than that required for real-time products, to allow for science and engineering research studies, and for developing wave atlases and climatologies subsequent to the initial deployment.

8. Communications

Communication systems can be simple, especially for small buoys using cell phones and/or cable. Coastal buoys are likely to require VHF or UHF line-of-sight radio, or RF satellite links; deep sea buoys are likely to require RF satellite links using such systems as Iridium, Inmarsat, GPRS, etc.

9. Data Products

A variety of wave buoy products support the maritime industry [3]. Examples include wave height and period probabilities, wave slope, recent observations, wave spectra, and time series. Parameters include wave height, wave period, and direction. Wave height is usually reported as significant wave height. This value is approximately the average of the highest 1/3 waves, which is not the highest wave that a mariner will encounter. The upper end of the range is approximately 1.5 times the significant height. This is closer to the largest swell that may occur during a forecast period. Dominant and average wave period tend to be reported. Wave direction is reported in degrees. These products improve navigation by providing knowledge of prevailing sea-state conditions. Marine operators use these data to understand the dynamic behavior, safety, and operability of ships in the vicinity of the buoy. Thus, access to real-time wave measurements 24 hours a day and seven days per week increases safety and the effectiveness of sea transport. Products cannot be developed during buoy outages which are generally caused by:

- mooring failure
- collisions and broken hulls
- physical damage to electrical system components or critical sensors
- degraded cables (power and telemetry)
- lightning strikes that disable the electrical systems

Some of these failures are related to vandalism, which has to be considered in selecting sites.

Many times, buoy deployments are designed to satisfy several users with varying requirements [5], such as operations, monitoring, and research. These requirements must drive the raw data transmission vs. onboard processing considerations. Raw data are seldom of immediate value unless quality control is included in the data acquisition software. Time series of short records with high resolution may be needed for high wave conditions, longer time series giving good statistical stability are also needed for calculation of products, such as significant wave height, wave steepness, dominant wave direction, height-direction histograms, non-directional and directional spectra. Modern algorithms such as maximum entropy facilitate calculation of spectra using relatively short time series. Wave characteristics can often be calculated on relatively short time series using FFT techniques, allowing for a good compromise between resolution and statistical stability.

10. Conclusions

One must consider environmental factors when selecting the optimal wave buoy for a particular site. Based on mooring location, the user will pick the appropriately sized and shaped hull. Sizes will range from mini drifting data buoys to large 12-m diameter discus buoys. Buoys tend to have sphere, saucer, and boat shaped hulls. The moorings are designed based on hull type, location, and mooring depth. Smaller buoys may be deployed in shallow coastal waters using an all-chain mooring, while a large discus buoy may be deployed in the deep ocean using a combination of chain, nylon, and buoyant polypropylene materials. Coastal buoys should be deployed in deep enough water that they are well outside of the surf zone.

A great number of applications of buoy technologies exist, too numerous to be all inclusive, but some of the most common are listed below:

Forecasting- Weather forecasters require information from the oceanic and coastal areas for data input to forecast models. Deep sea and coastal buoys are required in sufficient numbers to provide data to model grid points for such applications as storm surge predictions. Without an adequate network of meteorological/oceanographic buoys, good predictions of severe coastal and tropical storms cannot be made.

Model Validation and Data Assimilation - Researchers involved in the development and testing of wave models require high quality data for model validation, and to determine boundary conditions. Usually directional wave and wind information is required at specific locations corresponding to model grid points and boundaries.

Storm Surge – Forecasters concerned with the protection of life and property want as much warning time as possible. Deep sea and coastal buoys with wind and wave sensors in the appropriate spectral bands are needed for these applications. Extreme ruggedness of buoys and components is a requirement of this application.

Navigation & Ship Routing – Marine pilots benefit greatly from coastal and inshore buoys providing winds, waves, and currents for navigation of large commercial vessels from offshore to dockside. Ship routing organizations require winds and waves at several locations in the deep ocean to run their models. The data for this application usually dictate the deployment of deep sea and coastal buoys equipped with wind velocity, directional wave, and current sensors.

Search & Rescue – Search and rescue teams require real-time information at critical locations in marine and freshwater environments to develop deployment and search strategies, and to implement those strategies. Data at specific locations may be needed to refine the search and assess possible drifting scenarios. Floating directional wave and current buoys would be needed at these specific sites.

Military – The forces often require environmental information at remote and little-known sites for special operations. Small, lightweight buoys reporting winds, waves, temperature, salinity, and transmitting data in real-time are required. The buoys should be deployable from aircraft, small boats, submarines, or by divers.

Drug Interdiction & Police Work – Real-time information on winds, waves, and currents is needed for drug interdiction missions. Anchored buoys at known critical sites, and small, easily deployed floating buoys to provide real-time data would be ideal to transit to drop sites and to interdict the perpetrators.

Environmental Assessment – Monitoring environmental dynamics and water quality necessitate long-term deployments of months to years. Coastal and protected water buoys are needed in coastal, estuarine, river and lake environments. Real-time information is usually not so important as adequate temporal and spatial coverage, and choosing the key parameters.

Marine Spill Response – In the event of oil or other spill at sea, equipment operators, managers, and first responders such as the Coast Guard require real-time data on winds, waves, currents, and temperatures to plan and direct clean-up operations. Coastal and smaller buoys can all be brought into play to provide the necessary data.

Recreation and sporting events – Coastal buoys with wind velocity, directional wave, and current sensors reporting in real-time can be deployed to complement existing buoy networks in events such as sail boat races, the “Iron Man” and other long-distance swimming events. During the Bermuda Races, deep ocean buoys provide data on weather, currents (including Gulf Stream eddies and rings), and enable skippers to plot their best time routes.

Coastal & Structural Engineering – Marine structures, such as piers, breakwaters, oil drilling platforms are designed by ocean engineers and naval architects who require climatological wave data in the design phase, and real-time data in the deployment and data acquisition phase. Wave data is needed in real-time during oil drilling platform operations to provide for crew safety, and to prevent damage to equipment. Coastal buoys reporting wind velocity, wave height, and direction, and currents can greatly enhance safety and prevention of spills. As marine mineral extraction moves steadily from the continental shelves to the continental slopes deep ocean buoys are required to provide a safety net to the engineers, technicians, and crews

Fishing & Bio-Assessments – Fishing vessels are often small and/or not well equipped to deal with extreme weather events at sea or on large lakes. Deep sea and coastal buoys supporting wind velocity, directional wave, and current sensors can provide a measure of safety to the fishing fleets by providing early warning, and enabling accurate forecasts of wind and sea condition. Anchored deep sea and coastal buoys in the weather forecasting networks are most useful in this setting. These buoys should also support temperature sensors which are very useful for locating schools of fish.

Research – Buoy-based programs for climate prediction, tsunami detection, and undersea volcano detection require buoy data at all spatial and temporal scales. Toroidal buoys have been and are being deployed in the equatorial currents to map such features as the El Nino. Studies of the energy flux between air and sea require wind, wave, current, temperature, salinity, solar radiation, and other data. Deployment times range from months to years for climatological studies, so that power and maintenance intervals become very important considerations.

Choosing the right wave buoy for the right job requires a careful statement of requirements consistent with providing the essential data on time and at cost or below. Whether the application is for river, lake, coastal, or deep sea monitoring, a wide variety of buoys and sensors is available to get the job done, and provide data for follow up scientific and engineering analysis which may benefit future generations of mariners and all those drawn to the sea.

11. Acknowledgment

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